POLYGON SCANNER FOR LASER PAINT STRIPPING

Paper (1302)

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Abstract

Many vehicles and structures require removal of existing paints and/or coatings. Traditional paint removal methods utilize toxic solvents and media blasting, both of which create a multiplication of resultant hazardous waste. Other paint removal technologies involve thermal processes, such as flash lamps and CO_2 bead blasting, in conjunction with each other or separately. For many years the Air Force, NASA, Navy, DOT, and other government agencies have been investigating laser stripping for a multitude of coating removal challenges. Several high-power (multi-kilowatt) laser paint stripping systems have been built for these agencies, and some are currently operating in evaluation and production modes. The most recent laser coating removal systems have been based on some form of beam scanning technology to create the required energy delivery (power density, travel speed, exposure time, etc.) to the work surface. Unfortunately, the current scanners used to accomplish this task are large, heavy, inefficient, and somewhat power limited. EWI has recently developed a new scanner solution that solves all of these problems. Laser paint stripping efficiency and productivity with this new polygonal scanner technology are shown to be 2 to 3 times higher than previously reported values.

Introduction

Paint and other coatings are everywhere in our lives, and they have a multitude of uses. We paint surfaces for their protection and for their appearance. We paint objects to make them more obvious or less obvious. And, of course paint can become art. But, paint doesn't last forever. It can peel, erode, flake, crack, or become unwanted for a variety of reasons. In many cases the removal of old paint is a critical step in the long term preservation of infrastructure assets, such as bridges, storage tanks, rail cars, etc. Sometimes we just want a new color on our painted surfaces. Imagine, for instance, the paint removal challenge that an airline faces when it acquires a competitor's fleet of aircraft.

Paint removal can be accomplished in variety of ways, but the dominant two methods are media blasting and chemical removal. Sand is certainly the most common media for the blasting solution, and painted steel surfaces are the most common application for it. We've all seen the tents around bridges during repair and repainting. For softer substrates, such as aluminum, media blasting is carried out with plastic beads, walnut shells, starch, or even CO_2 pellets. Alternately, chemical paint stripping is widely used on aircraft and off-aircraft components. The chemicals used for paint stripping have been improved over the years, but they remain toxic and hazardous in various degrees. Additionally, media blasting and chemical paint removal techniques both multiply the amount of hazardous waste that must (or should) be managed, and they present a variety of worker hazards. This combination of environmental and worker safety issues demands a "greener" solution to the challenge of coating removal.

Laser Paint Stripping Background

The Air Force has been pursuing alternative paint removal techniques for decades. Their needs are strategic, and their aircraft present some unique paint removal "business cases". Thus, the Air Force has been the driving force in the investigation and development of laser paint stripping technologies. A number of Air Force projects from the 1980s demonstrated the potential of laser paint stripping and at the same time identified the implementation challenges to come. Not the least of these challenges was the somewhat restrictive nature of large area manipulation for high power, CO_2, laser beams. Still, as lasers became more "industrialized," and beam delivery became better managed, the development of laser paint stripping technologies continued, resulting in several installations of laser de-painting facilities at Air Force bases. The current Air Force laser paint stripping installations serve as demonstration <u>and</u> production facilities, even as the fundamental paint stripping technologies continue to evolve.

Most of the early, large area, laser paint stripping development was carried out with CO_2 lasers of one type or another. Continuous wave, TEA laser, and e-beam pulsed lasers were among those evaluated. The far-infrared wavelength of these lasers is attractive from the standpoints of absorption by the paint and substrate damage resistance, but, as mentioned above, the beam delivery complexity of CO_2 lasers encumbered some of the potential applications. Despite this complexity, the multi-kilowatt power capability of these CO_2 lasers established attractive benchmarks for paint removal rates and efficiencies. The paint stripping rates of these demonstrations made the business cases for laser paint stripping credible, and interest in the technology survived. So, when robust, multi-kilowatt, fiber-delivered (1.06-1.07 um), laser power became available in recent years, additional research was undertaken to evaluate this "new" candidate wavelength regime.

The physical mechanisms of laser paint stripping have been described in a number of ways, including vaporization, ablation, combustion, multi-photon absorption, shock removal, etc. Figure 1 shows the substantial range of peak power and interaction times over which laser paint stripping has been accomplished.

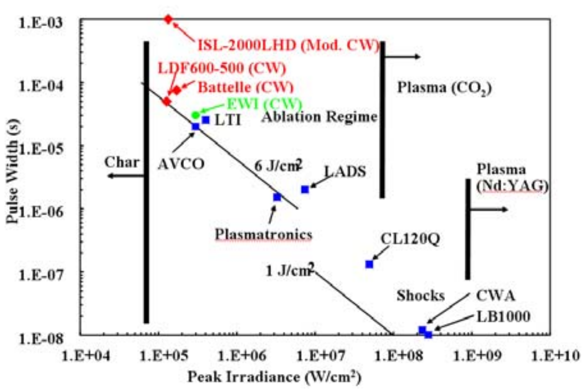

Figure 1. Range of peak irradiance vs pulse width for laser paint stripping trials over 25 years.

The "bottom line" here is that there are many physical mechanisms/interactions that can be applied, but some are more implementable and affordable than others. Regardless of the mechanism, one fundamentally important requirement is that the laser power be delivered in an intense, short time period, in order that the delivered energy remains primarily contained in the removed paint and not transmitted or conducted to the substrate. This requirement can be fulfilled with a pulsed beam or with a rapidly scanning beam, both of which can successfully limit the local interaction time of the beam with the work.

Considering that continuous wave laser power is usually more powerful, affordable, and robust than pulsed laser power, it is not surprising that the use of a beam scanner to produce the required, short, interaction time with the work is an attractive solution. Indeed, this is the solution that the Air Force and others have been pursuing in the last few years. Galvo and servo-motor-driven scanners have both been evaluated for this purpose, but the former has achieved the greater success. Figure 2 illustrates the general orientation of galvo scanning mirrors in a typical laser paint stripping configuration.

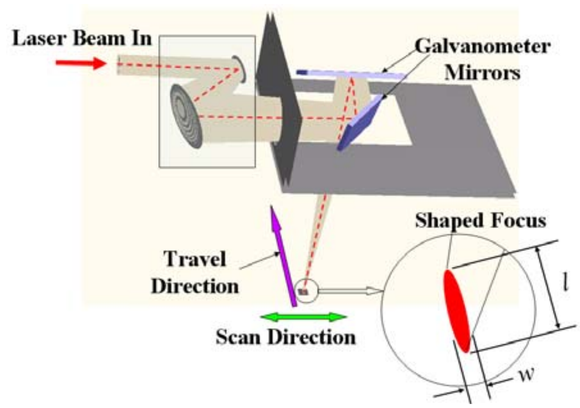

Figure 2. Typical galvo configuration for laser paint stripping.

Of course galvo scanners have achieved their greatest success in the low power marking applications, but galvos face some significant limitations in the multi-kilowatt regime, where laser paint stripping is most attractive. As the laser power increases, the galvo scanning mirrors become heavier, and the scanning speed and acceleration decrease. This is true even in the case of a single axis galvo with travel motion provided by another mechanical axis. Typical maximum scanning speed for continuous, high-power, large area, galvo scanners is in the 10 m/s range, which results in a longer-than-optimal interaction time with the work surface. High power galvos also tend to be heavy and require long focal lengths to accomplish required scan widths. For these reasons and others, EWI and Craig Walters Associates (CWA) undertook a joint project to develop a polygon scanner for high power laser paint stripping.

Polygon Scanner Design

Polygon scanners had been investigated for laser paint stripping as early as 1986, when Craig Walters, then at Battelle, used a polygon scanner that the authors had originally designed and built for laser surface cladding and heat treating. This scanner (Figure 3) successfully performed CO_2 laser paint stripping and established some of the early benchmarks for paint stripping efficiency and productivity. Nevertheless, this early solution for laser paint stripping was not pursued at that time or for the ensuing two+ decades.

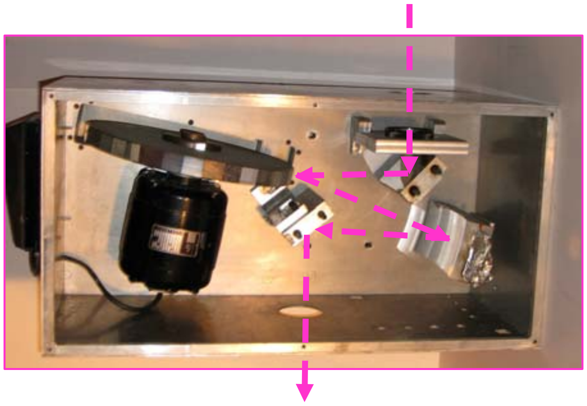

Figure 3. Early (1986) polygon scanner developed by Walters and Ream at Battelle

Then, in 2009, as the Air Force appeared to be ramping up their interest in laser paint stripping, EWI and CWA concluded that it was time to re-invent polygon laser scanning. It was believed that by taking advantage of all the advancements in laser and optics technology that had occurred in the intervening years, a much more capable scanner could be developed.

Initial design work was greatly facilitated with modern computer aids, including, AutoCad™, ZEMAX™ and SolidWorks™. The initial results of the first, patent-pending, design efforts are shown in Figure 4. The specific deployment shown here utilizes a fiber-delivered beam, but alternate solutions have been developed for CO_2 laser input. The EWI scanner has only one moving part, the polygon itself, which rotates at a constant velocity and produces a unidirectional, essentially constant velocity path on the work surface. Using only a modest rotational speed, the polygon scanner can produce a surface scanning velocity exceeding 50 meters per second. This high scanning speed permits short interaction time of the beam with the work surface and allows very high laser power to be utilized.

One particularly unique and important aspect of this design is the absence of a transmitting protective window, such as those found in typical galvo scanners. Transmitting windows have a low tolerance to contamination, are subject to thermal lensing at high power, and can be very expensive in CO_2 applications. Instead, the EWI polygon scanner takes advantage of a cross-over location in the scanning beam path, which facilitates the incorporation of an aerodynamic window. Thus, clean dry air or nitrogen can be introduced into the scanner enclosure to produce an outward gas flow through the aero window to thwart the ingress of contaminants. Additional design synergy was achieved by using a nitrogen gas nozzle to rotate the polygon, thus accomplishing cooling as well as gas flow for the aero window.

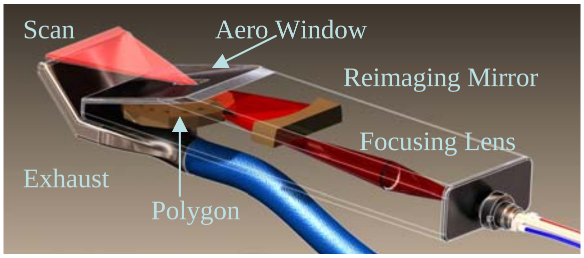

Figure 4. EWI patent-pending polygon scanner design

While this initial design was straightforward, compact, and light weight, some motion system deployments (i.e. robots, gantries, etc.) suggested that a right angle between the input beam and the scanned beam would be preferable. Additionally, since the scanner would eventually be required to deliver 10 to 15 kW of laser power, replacement of the focusing lens with a focusing mirror was considered desirable.

The second design iteration of the EWI polygon scanner replaced the focusing lens with a right angle focusing mirror (Figure 5). To the best of our knowledge, such a mirror had never been produced for high-power laser materials processing applications. EWI, CWA, and the highly accomplished optics manufacturer, II-VI, collaborated for some time before coming to a solution that the team loosely called an "asymmetric asphere".

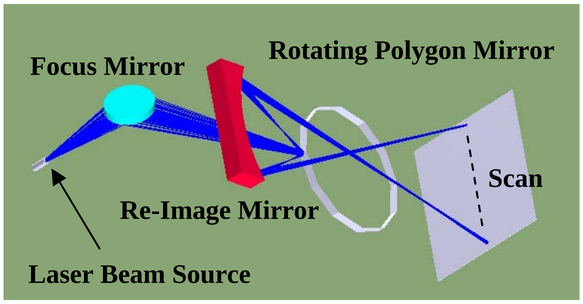

Figure 5. Fully reflective polygon scanner design

The eventual SolidWorks design details for this apparent, first-of-a-kind, focusing mirror (as well as the polygon and re-imaging mirror) were transmitted to machine tool builder, Wayne Trail Technologies (WTT) for production of the copper mirror blanks.

The same information was also transmitted to II-VI for their use in the building of tooling related to the subsequent diamond turning of the three optics. Remarkably, this fully electronic creation, coordination, and e-mail transmission of precision optical surface information among the CWA-EWI-WTT-IV-VI team members resulted in optical performance that actually exceeded the team's expectations.

The most surprising optical results were those achieved by the asymmetric asphere focusing mirror. The focus characteristics of this mirror were measured using a Primes focus monitor, the results of which are show in Figure 6.

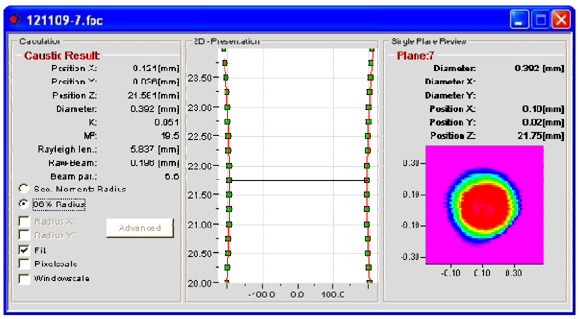

Figure 6. Asymmetric asphere focusing quality

The results in Figure 6 were obtained using EWI's, then 10 kW, IPG, fiber laser with a 200 um delivery fiber. The beam parameter product of 6.6 mm-mrad for this focusing optic is better than any other commercial or custom focusing optic (transmissive and/or reflective) previously measured by EWI using this laser. Closer examination of the focal spot shape (Figure 7) may help explain this exceptional measurement.

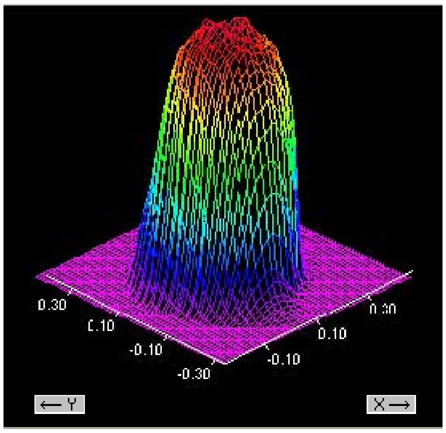

Figure 7. Focal spot shape from asymmetric asphere

Even though the optical solution for this focusing mirror evolved from a re-imaging design, the more typical flat-top power distribution of the fiber end was not reimaged at focus as completely as has been seen in other optical focusing systems. Whether through great design or just great luck, this result was a welcome finding for this risky, first-of-a-kind optic.

The remaining optics, polygon and reimaging mirror, also performed exactly as planned, and the prototype scanner (Figure 8) was assembled for paint stripping tests.

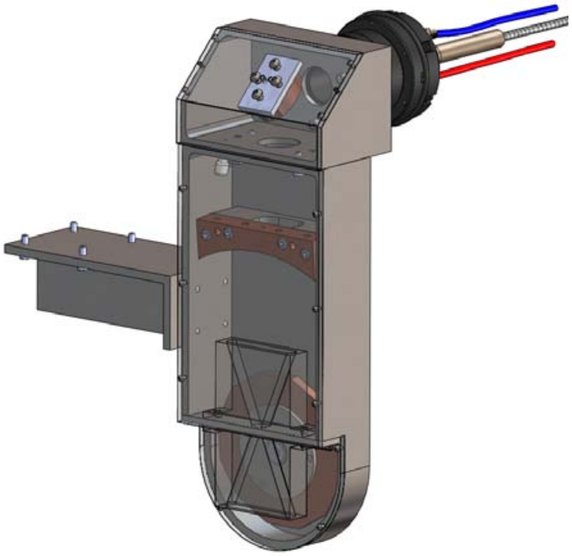

Figure 8. Solid model of prototype polygon scanner, EWI patent pending

Polygon Paint Stripping Performance

Large area paint stripping results with the EWI scanner have exceeded expectations. Comparisons of "normalized stripping rate" with previously reported, benchmark, laser paint stripping efforts (Figure 9) clearly illustrate this point. The metric here (normalized stripping rate, R_n) is essentially a measure of laser paint stripping process efficiency, specifically it is the volume of paint removed per amount of energy delivered, expressed as:

Rn = paint volume removed / energy input, or

Rn = square feet * mil of paint / kW minute

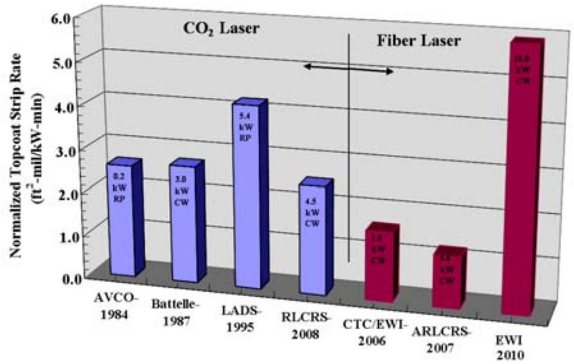

Figure 9. Normalized strip rates on typical aircraft paint

Considering further that the EWI scanner has applied the highest and most efficient laser power to date for paint stripping purposes, this advancement is indeed remarkable. The net result of this total applied laser power and the improved paint stripping process efficiency is that the EWI polygon laser scanner can remove paint nearly three times faster than any other reported laser paint stripping technology (Figure 10).

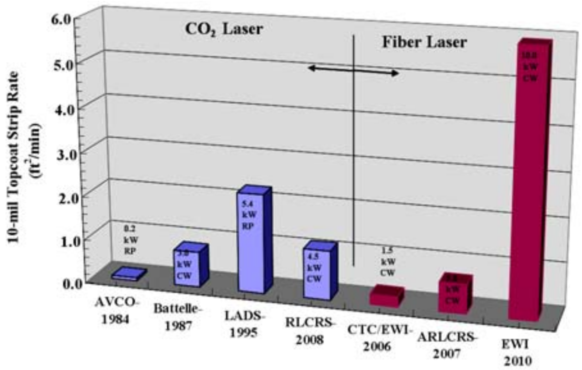

Figure 10. Laser paint stripping rates on typical aircraft paint

<u>Legend:</u>

AVCO: AVCO Everett Research Laboratory, 3 kW, pulsed CO_2 laser, decommissioned.

Battelle: Battelle Memorial Research Institute, 5 kW, Spectra Physics, continuous wave CO_2 laser with polygon scanner, decommissioned.

LADS: Laser Automated De-coating System, 5kW, pulsed, custom laser, at Hill Air Force Base, decommissioned.

RLCRS: Robotic Laser Coating Removal System, 6 kW continuous wave, Rofin-Sinar CO_2 laser, galvo scanner, at Tinker Air Force Base.

CTC/EWI: Concurrent Technologies Corp testing at EWI, 1.5 kW from 4 kW, IPG fiber laser with SCANLAB galvo scanner.

ARLCRS: Advanced Robotic Laser Coating Removal System (prototype), 5 kW continuous IPG fiber laser, galvo scanner, at CTC, Johnstown, PA.

EWI: Current work at EWI reported here.

In additional to the high paint removal efficiency and overall stripping rate, serendipity was realized in the daunting area of effluent removal. One of the substantial issues at the onset of this scanner development was the concern that higher laser power would result in an unmanageable amount of effluent, i.e. flaming gas and particulate, since other high-power laser paint stripping efforts had encountered significant difficulty in this area.

Fortunately, at the high scanning speeds available with the polygon scanner, the effluent evolution during each scan sweep is able to be swept away with a modest (~12 m/s), vacuum-induced air flow (Figure 11). A theory of this effluent manageability was developed when tests were conducted at lower focal spot scan speeds (~15 m/s). At the lower scan speeds the flame height increased substantially, and the collection nozzle was unable to remove all of the effluent. Thus, it appears that effluent velocity and/or momentum is somehow inversely proportional to scan speed. Additionally, high speed, diode illuminated video revealed this efficient sweep-by-sweep removal of effluent. In summary, the high focal spot travel speed of the polygon scanner produces a "shorter", less energetic effluent stream, which can be easily swept away with the exhaust flow.

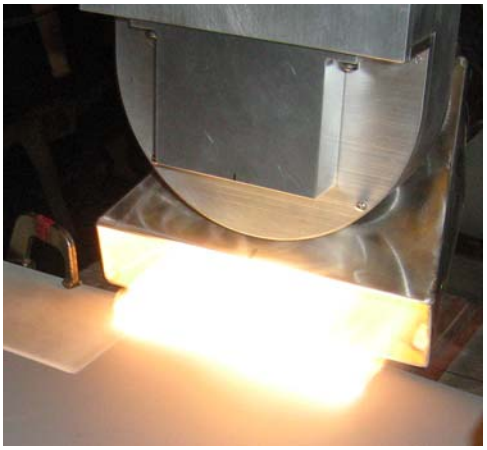

Figure 11. Manageable paint stripping effluent

Not only is the effluent removal highly manageable with the EWI scanner, but the resulting solids in the effluent stream appear to be completely "dry" rather than the sticky agglomeration that others have reported. Much study remains to be performed in the overall effluent management area, but it is reasonable to conclude that this version of laser paint stripping produces a near minimum of solid waste.

On the other hand the efficiency and manageability of effluent removal comes with a challenge. Measurements of the flow volume and exit temperature of the effluent stream (during 10 kW paint stripping) suggest that as much as 50 to 60 kW of thermal power is being successfully removed from the laser interaction region. This net combustion power must be managed, primarily through "dilution" with additional post-combustion air, in order that conventional exhaust tube materials can be utilized. Fortunately, close observation of the flame inside the exhaust nozzle suggests that combustion is substantially complete within a few inches of the part surface. This observation greatly simplifies the solution to this rather large power management challenge.

Summary Accomplishments

The benefits and advantages of the EWI polygon scanner technology for large area laser paint stripping are numerous and are summarized briefly below.

- Highest paint stripping power capability
- Available for multiple laser wavelengths
- More robust than other scanners
- Light weight for easier manipulation by robots and other motion systems
- Aero window eliminates need for consumable transmitting windows
- Highest reported laser paint stripping process efficiency
- Highest reported laser paint removal rates
- Facilitates efficient, complete, effluent removal

In the overall scheme of a potential laser paint stripping system or facility, the scanner itself would be a fairly small and relatively low cost component. Still, the above advancements in the core laser paint stripping process technology are essential for the creation of stronger business cases for specific applications. For instance, the higher stripping efficiency and the lighter weight of the polygon scanner mean that the motion systems required for large paint stripping jobs (airplanes, ships, etc.) can be faster and lower cost. And, given the higher effective paint stripping rates of the polygon scanner, the overall productivity of the paint stripping facility can be higher. For these and other reasons, this enabling piece of laser paint stripping technology substantially enhances the business cases for a multitude of potential applications.

Future Work

As encouraging as these results are, several areas of required, additional development remain to be satisfied. Most important among them is the need for development of a process control technology. Specifically, it is essential that the overall laser scanner "system" be capable of monitoring and controlling the laser paint stripping process so that the correct amount of paint is removed from the intended location. Many solutions for this control requirement have been conceived; some have been patented; and, some have been applied. Candidate control solutions for application to EWI's polygon scanner technology are under investigation, and success in this area is considered to be attainable in the near future. Continuing advancements in sensors, cameras, and computing power make this essential task much simpler and more affordable than in the past.

In conclusion it is reasonable to state that all the required elements for successful, industrial, laser paint stripping application have been developed or are within our reach. Much work remains to be done, but the path forward is clearer today than ever before.

Acknowledgments

EWI gratefully acknowledges the contributions and collaboration with the following individuals and organizations:

- Dr. Craig Walters, co-developer of the EWI polygon scanner and widely-recognized leading expert in laser paint stripping technology.

- II-VI Incorporated and specifically Gary Herrit, for his essential contribution to the focusing optic figure solution.

- Wayne Trail Technology for their precision machining of all the components in the prototype fabrication.

- Air Force Research Laboratory and Tom Naguy specifically for his support (through CTC) of the initial demonstration of EWI's polygon scanner technology.

Meet the Author(s)

Stan Ream is the Laser Technology Leader at EWI and an internationally recognized expert in laser materials processing technologies. Dr. Craig Walters is the President of CWA, providing laser physics and engineering consulting services to a broad range of government and industry clients, including EWI.